DOCUMENT RESUME

ED 404 098 SE 052 887

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TITLE Designing Curricula for Conceptual Restructuring: Lessons from the Study of Knowledge Acquisition in Astronomy.
INSTITUTION Illinois Univ., Urbana. Center for the Study of Reading.
SPONS AGENCY National Science Foundation, Washington, D.C.; Office of Educational Research and Improvement (ED), Washington, DC.
REPORT NO TR-546
PUB DATE Mar 92
CONTRACT G0087-C1001-90; NSF-BNS-85-10254
NOTE 26p.
PUB TYPE Reports - Research/Technical (143)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Astronomy; Beliefs; Cognitive Processes; *Cognitive Restructuring; *Cognitive Structures; *Curriculum Design; Curriculum Development; Elementary Secondary Education; Metacognition; *Misconceptions; *Science Curriculum; Science Education; Science Instruction; Scientific Concepts; Student Characteristics
IDENTIFIERS *Mental Models

ABSTRACT

This document examines children's and adults' knowledge of observational astronomy and characterizes the kinds of mental models students form when asked questions in astronomy. Mental models were grouped into three categories: intuitive, synthetic, and scientific. Implications for the design of curricula and for instruction are identified. In designing curricula in domains where learning requires the restructuring of prior knowledge, particular attention must be paid to the sequence in which the various concepts that comprise a given domain are introduced. It is suggested that instruction consistent with the sequence of acquisition of these concepts will be more successful than instruction that is not. The texts written should provide adequate explanations of the scientific concepts that are introduced, explanations that take into account the mental models and entrenched beliefs the students may have based on their everyday experience. Particular attention must be paid to providing students with situations that make them realize that what they may consider as facts about the world may be interpretations subject to falsification, and that sometimes there can be good reasons for replacing their existing beliefs with a new explanatory framework. Contains 35 references. (Author/MDH)

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ED 404 098

CENTER FOR THE STUDY OF READING

Technical Report No. 546

DESIGNING CURRICULA FOR CONCEPTUAL RESTRUCTURING: LESSONS FROM THE STUDY OF KNOWLEDGE ACQUISITION IN ASTRONOMY

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March 1992

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The work upon which this publication was based was supported in part by Grant No. BNS-85-10254 from the National Science Foundation, and in part by the Office of Educational Research and Improvement under Cooperative Agreement No. G0087-C1001-90 with the Reading Research and Education Center. The publication does not necessarily reflect the views of the agencies supporting the research.

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Abstract

In designing curricula in domains where learning requires the restructuring of prior knowledge, particular attention must be paid to the sequence in which the various concepts that comprise a given domain are introduced. Instruction that is consistent with the sequence of acquisition of these concepts will be more successful than instruction that is not. The texts written should provide adequate explanations of the scientific concepts that are introduced, explanations that take into account the mental models and entrenched beliefs the students may have based on their everyday experience. Finally, particular attention must be paid to providing students with situations that make them realize that what they may consider as facts about the world may be interpretations subject to falsification, and that sometimes there can be good reasons for replacing their existing beliefs with a new explanatory framework.

DESIGNING CURRICULA FOR CONCEPTUAL RESTRUCTURING: LESSONS FROM THE STUDY OF KNOWLEDGE ACQUISITION IN ASTRONOMY

Science Learning Requires Conceptual Restructuring

Research in cognitive science has demonstrated the importance of prior knowledge in the acquisition of new information. Our ability to learn something new depends critically on the interaction between the information that currently exists in the knowledge base and the new information to be acquired. When there are gaps in the knowledge base or when the prerequisite information has not been activated, the result is failure in communication and in learning (e.g., Anderson & Ortony, 1975; Bransford & Franks, 1972; Bransford & Johnson, 1972; Pichert & Anderson, 1977).

Unfortunately, in science learning, the prior knowledge that students bring to the knowledge-acquisition task is not always compatible with the new information that needs to be acquired. This is the case because science-naive individuals construct intuitive explanations of physical phenomena that are based on their everyday experience and that are often very different from the currently accepted scientific explanations. For example, in the area of mechanics, many students believe that a moving body has a force in it and that the movement of the object is caused by that force (e.g., Ioannides & Vosniadou, 1989; McCloskey, 1983). In the area of light, students believe that their eyes perceive objects directly and that color is a property of the objects themselves (Anderson & Smith, 1986).

In the process of learning science, students must restructure their intuitive knowledge to make it conform to the currently accepted scientific ideas. This process of conceptual restructuring has proven to be a long, difficult one and one that has the potential of giving rise to misconceptions (e.g., Driver & Easley, 1978; Novak, 1977; Osborne & Wittrock, 1983). For example, even after a number of years of high school physics and/or a university physics course, many students cannot understand Newtonian principles of motion but adhere to their earlier beliefs that are more consistent with everyday experience (e.g., diSessa, 1982; White, 1983).

How Do We Design Curricula to Bring About Conceptual Restructuring?

The realization that some forms of learning require the radical restructuring of prior knowledge raises important questions about curricula and methods of instruction. Should students be taught the most advanced scientific theories from the beginning? What is the best sequence of concepts for students to acquire when they obtain knowledge in a domain? What are the best methods of instruction when a scientific concept is radically different from the intuitive knowledge that already exists in the knowledge base? (See Vosniadou & Brewer, 1987, for a more extensive discussion.)

There is currently a lot of debate about how best to characterize the nature of intuitive knowledge and about the ways in which it can be modified. Some researchers believe that novices' ideas can be conceptualized as consisting of a coherent and systematic set of ideas that have a status similar to that of a scientific theory. In some cases, these ideas are found to resemble earlier theories in the history of science (McCloskey, 1983; Wiser & Carey, 1983). Other researchers think that naive physics consists of a fragmented collection of ideas that are loosely connected and do not have the systematicity one attributes to a scientific theory (diSessa, 1988).

Depending on one's beliefs about the nature of intuitive knowledge, different instructional implications are drawn. Researchers who view novices as having relatively well-organized and consistent naive theories think that the process of science learning requires a change in theory similar in some respects to the kind of theory change observed in the history of science (Hanson, 1958; Kuhn, 1962, 1970). Although the mechanisms for achieving this kind of theory change are not yet known, most of these

researchers believe that it is necessary to confront the novice students with enough evidence to make them realize the limitations of their theories and to change them (e.g., Anderson, 1977; Collins, 1986; McCloskey, 1983; Nussbaum & Novick, 1982).

Other researchers (e.g., diSessa, 1988) think that a one-by-one attack on the knowledge fragments that constitute intuitive physics is a hopeless task. They suggest that what is needed is to use these fragments to develop the science understanding that science-naive individuals lack. For example, diSessa proposes developing ways to collect and unify intuitive knowledge through microworlds.

I believe that the answers to these instructional questions need to be based on empirical research aimed at describing the process of knowledge acquisition in a given domain and at identifying the mechanisms that bring about the observed developmental changes. In this report, I will discuss the results of such a research program in the domain of astronomy and will draw their implications for the design of curricula and for instruction. Very briefly, my recommendations emphasize the importance of designing curricula that (a) present the concepts that comprise a given domain in a sequence consistent with the order in which these concepts are acquired, (b) create circumstances for students to question their existing beliefs, and (c) provide clear explanations of scientific concepts.

Conceptual Restructuring in Astronomy

The Astronomy Research Project

My colleagues and I have conducted a series of experiments investigating children's and adults' knowledge of observational astronomy. These studies have involved preschool, elementary, and high school children; college undergraduates; and adult illiterates (Brewer, Hendrich, & Vosniadou, 1988; Vosniadou, 1987, 1989; Vosniadou, Archodidou, & Kalogiannidou, in preparation; Vosniadou & Brewer, 1990, submitted). In addition to studies conducted in the United States, we have collected data from children and adults in India, Samoa, and Greece. These studies have provided us with specific information about children's and adults' knowledge about the size, shape, movement, temperature, composition, and location of the earth, sun, moon, and stars, and their explanations of phenomena such as the day/night cycle, the seasons, the phases of the moon, and the eclipses of the sun and the moon.

We selected the domain of observational astronomy because we believed that the knowledge-acquisition process in this domain requires conceptual restructuring. This is the case, because even very young children have observational evidence about the shape, size, movement, and location of the earth, sun, moon, and stars that runs contrary to current scientific views. For example, our phenomenal experience of the earth is that it is flat, stationary, much bigger than the sun or the moon, and located at the center of the universe. If students construct intuitive models of the cosmos based on their everyday experience, their models will be very different from the accepted scientific theories and will need to be restructured when exposed to the culturally accepted views. The purpose of our research was to understand the process of conceptual change.

Mental Models

I have adopted the construct of the mental model to characterize the kinds of representations students form when they are asked questions or solve problems in astronomy. The term "mental model" has been used in a number of different ways (e.g., Gentner & Stevens, 1983; Johnson-Laird, 1983; Stevens & Collins, 1980). It is used here to refer to a particular kind of mental representation that is different from other kinds of representations in that it is an analog to the state of affairs (perceived or conceived) that it represents (Johnson-Laird, 1983). I assume that mental models are generated from people's underlying conceptual structures, and that understanding the mental models individuals use to answer questions and solve problems can provide important information about the contents and structure of the knowledge base.

Our studies have shown that there is a limited number of mental models of the earth, the sun, the moon, and the stars that individuals construct. For example, in the case of the earth, my colleagues and I have shown that many elementary school students hold one of the six mental models shown in Table 1 (see Vosniadou, Archodidou, & Kalogiannidou, in preparation; Vosniadou & Brewer, submitted). Some students think that the earth is shaped like a rectangle. Others think that the earth is circular but flat like a disc. A few students think that there are two earths: a flat one on which people live, and a round one that is up in the sky. Others believe that the earth is a hollow sphere and that people live on flat ground inside it. Finally, some students think that the earth is flattened at the top and bottom where people live.

[Insert Table 1 about here.]

A number of different mental models of the day/night cycle have also been identified (Vosniadou, in press; Vosniadou & Brewer, in preparation). As shown in Table 2, some elementary school students believe that the change from day to night is caused because the sun moves down on the ground and hides behind the mountains. Others think that clouds move in front of the sun and block it. Some students who have a hollow-sphere mental model believe that the day/night cycle is caused because the sun moves from the sky, which is located inside the hollow sphere, to outer space, which is located outside the hollow sphere. One interesting model is held by students who think that the earth rotates in an up/down direction, and that the moon and sun are fixed at opposite sides of the earth. These children believe that the moon is fixed in some place in the sky where it is always night; as the earth rotates in an up/down direction, our part of the earth eventually comes to face the moon in the night sky (see Table 2).

[Insert Table 2 about here.]

The Identification of Students' Mental Models

Elementary school students' models of the various concepts investigated were identified from their responses to a number of questions tapping each concept. These questions were of three types: (a) *factual questions* designed to test the child's knowledge of theoretically important facts (e.g., "What is the shape of the earth?"), (b) *explanation questions* designed to lead the child to explain these facts (e.g., "How do you know that the earth is round when the earth around us appears to be flat?"), and (c) *generative questions* designed to capture the child's generative model (e.g., "If you were to walk for many days would you ever reach the end of the earth?"). Follow-up questions and confrontation questions were also used throughout the interview to try to understand children's beliefs.

Students gave a variety of responses to these questions. For example, some students said that the shape of the earth is a "rectangle," others a "circle," others "round." Some students said that there is an end to the earth, others that there is no end, and others that there is an end but that it cannot be reached because it is high up. Some students said that you look "down" to see the earth, some that you look "up." In many cases, the children's responses seemed to be internally inconsistent. For example, the same child who said that the earth is round could also claim that the earth has an end and that people can fall down from that end.

A question of particular interest was to determine whether students' responses to these questions were generated by a well-defined underlying mental model and to investigate the degree to which this mental model was used in a consistent way. To do that, a number of possible mental models were derived from our data as well as from previous research in this area (e.g., Nussbaum, 1979; Nussbaum & Novak, 1976; Sneider & Poulos, 1983). Then, for each question investigating a given concept the answers expected if the children had that model were generated. For example, it was reasoned that if the children believed that the earth is a sphere, they should say that the earth's shape is "round," that you look

"down" to see the earth, that there is no edge to the earth, and that if you were to walk for many days in a straight line you would eventually come back to where you started.

Once the pattern of responses for each model was determined, children's responses to the relevant questions were checked to see if they agreed with the expected ones. Placement in one of the models required no more than one deviation from the expected pattern and only if this deviation occurred in a non-defining item for that category. For example, a child who said that there is an end to the earth could not be assumed to have a spherical-earth mental model, even in those cases where this response was the child's only deviation from a spherical-earth model response pattern. On the other hand, the response "circle" to the question "What is the shape of the earth?" was considered an acceptable deviation for a child whose responses agreed in all other respects with the spherical-earth mental model.

We were able to determine students' models for about 80% of the cases for each concept investigated (see Vosniadou & Brewer, submitted). Some students had mixed models that contained elements from two or three individual models, and in a few instances no consistent model could be identified. Our success in identifying a few mental models of the earth that many students use in a consistent way indicates that students' knowledge base is not as fragmented as some researchers have argued. It appears that students try to synthesize the information they receive from adults and from their everyday experience into coherent mental models that they then try to use in a consistent fashion.

Three Kinds of Mental Models

Students' mental models in astronomy can be grouped in three distinct categories: *intuitive, synthetic*, and *scientific*. The defining characteristic of *intuitive models* is that they require as little deviation as possible from the natural world as is phenomenally experienced. They show no influence from adult scientific models. Such mental models are, for example, the model of a flat rectangular or disc-shaped earth and the model of the day/night cycle according to which the alternation of day and night is caused because the sun and the moon move down on the ground and hide behind hills or mountains.

Scientific models are the models held by educated adults in our society, the models that agree with current scientific views. *Synthetic models* show a combination of intuitive and scientific views, such as the view that the earth is a flattened sphere, or a hollow sphere with people living on flat ground inside it. Other examples of synthetic models are the view that night is associated with the moon, and the view that the stars, like the moon, take their light from the sun. Synthetic models are similar to what other researchers have called misconceptions. They represent some kind of misrepresentation of scientific information.

Entrenched Beliefs Constrain Students' Synthetic Models

Although the adult culture provides massive information to the idea that the earth is a sphere, many elementary school students come up with dramatic misconceptions regarding the shape of the earth. Why is this the case? In Vosniadou and Brewer (submitted), it was proposed that all synthetic models of the earth can be explained by assuming that students are operating under the constraints of two *entrenched beliefs*: The belief that the ground is flat, and that things, including the earth itself, will fall down if not supported.

In forming synthetic mental models, students change their intuitive mental models in a way that allows them to retain all or some of their experiential beliefs, without contradicting adult teachings. For example, the students who change their intuitive model of a *rectangular earth* to the synthetic model of a *dual earth* have retained almost all of the entrenched beliefs that gave rise to the intuitive model in the first place. These students answer questions in a way that shows that they still believe that the ground is flat, that the earth rests on ground or water, that people and other things live on flat ground, and that the sky is located only above the earth. The only thing that has changed is that they have

added to their knowledge base the information that there is another earth that is round like a ball and that is located up in the sky like a planet.

A detailed examination of students' responses reveals that there is a progression of more and more advanced synthetic models depending on how many entrenched beliefs the students have given up. For example, the hollow-sphere synthetic model is a more advanced one than the dual-earth model. The children who hold the hollow-sphere model have given up on their belief that the earth needs to be supported. These children conceptualize the earth as a sphere suspended in space, but they still believe that the ground is flat, and that the people and objects on the earth will fall if not supported. For this reason, they create a misconception that people live on flat ground inside the hollow sphere.

Lack of Metaconceptual Awareness

To explain how synthetic models are formed, it is helpful to consider the possibility that students lack the metaconceptual awareness necessary to question the truth or adequacy of their entrenched beliefs. If we assume that students view their entrenched beliefs to be unquestionable truths about the world, and not like hypotheses or assumptions in a scientific theory, then we can understand why they distort the scientific concepts to fit their entrenched beliefs, rather than the opposite.

In other words, the genesis of a synthetic mental model can be conceptualized in the following way. When students with an intuitive model of a flat and stationary earth read in a book or hear from a teacher or a parent that the earth is "round like a ball," they do not want to believe that the adult is wrong. However, the adult information is inconsistent with their entrenched beliefs that the ground is flat and that things fall down when they are not supported. Because students consider their entrenched beliefs to be obvious truths about the world (truths that are obvious to adults as well), they think that they have misunderstood what adults really mean. In trying to interpret counterintuitive information in a way that does not contradict their entrenched beliefs, students construct synthetic models.

Interdependencies Among the Concepts That Comprise the Domain of Astronomy

I have argued that students' entrenched beliefs constrain the kinds of mental models they can form. Understanding a scientific concept often requires students to reinterpret their entrenched beliefs. For example, understanding the scientific concept of a spherical earth requires students to reinterpret their belief that all things that appear to be flat are indeed flat.

In addition to students' entrenched beliefs, there is an interdependency among the various concepts that comprise the domain of astronomy, such that students' mental models of the earth may constrain their mental models of the sun, or the moon, etc. More specifically, it appears that the mental model of a spherical earth is a prerequisite to understanding the scientific explanation of the day/night cycle. In our studies, we have found that some students who understand the information that the earth rotates around its axis fail to see how this information explains the day/night cycle because they lack a spherical model of the earth. For example, one of our students constructed a disc model of the earth such as the one shown in Table 3A. This child understood that the disc earth turns in circles but, justifiably, could not see how this movement explained the disappearance of the sun at night. He therefore thought that the sun moves down and hides behind the mountains as well.

[Insert Table 3 about here.]

Another child with a hollow-sphere model created the synthetic model of the day/night cycle presented in Table 3B. According to this model, there is a hollow sphere that consists of two hemispheres: the lower hemisphere that represents the earth on which people live and the upper hemisphere that represents the sky covering the earth like a dome. The sun and moon are located at two opposite

sides--a day side and a night side--within the upper hemisphere. As the earth turns people move from the night side to the day side of the earth, and this is how we have a day/night cycle.

These examples show that there is an interdependency among the various concepts that comprise the domain of astronomy. Information is interpreted in the context of the mental models students already have. When these mental models differ from those required for the accurate interpretation of the new information, then the new information will very likely be misrepresented to fit the existing model.

Implications for the Design of Curricula and for Instruction

Although the studies my colleagues and I have conducted are not longitudinal but cross-sectional, the developmental patterns we have obtained indicate that the process of knowledge acquisition does not involve a sudden and dramatic shift, but it is slow and gradual. It appears that students start by constructing initial mental models based on everyday experience, and that they gradually modify these models to become consistent with the culturally accepted scientific views.

A very important role in the knowledge acquisition process is played by those modules of knowledge that appear to be the fundamental ingredients of naive knowledge and that we have called *entrenched beliefs*. Students' entrenched beliefs constrain the kinds of mental models that can be formed and lie at the root of their synthetic models or misconceptions. Given the highly intricate web of interrelations that exist among the various concepts that comprise a given domain, it is possible that the presence of a small number of entrenched beliefs can cause misconceptions that affect students' interpretations of a wide variety of problems, as was discussed in the previous section.

In view of the above, it appears that in designing curricula, we should be very careful about the order in which we introduce the various concepts that comprise a given domain. I believe that curricula that utilize the empirical information available about the order of acquisition of the concepts in a given domain will have a better chance of producing conceptual change than those that do not. In addition, particular attention should be placed on dealing with students' misconceptions and, of course, with their entrenched beliefs. It is not yet clear what are the best methods for changing students' entrenched beliefs, but I will offer some conjectures on the basis of the currently available evidence.

In this section, I will discuss the implications that our basic research findings have for the design of curricula and for instruction. At times, I will compare and contrast my suggestions with examples from astronomy curricula currently available for elementary school students. These examples come from an in-depth analysis I conducted recently of the astronomy units in four leading science series for the elementary grades.

Sensitivity to the Order of Acquisition of the Concepts That Comprise a Given Domain

The design of curricula should be based on knowledge of the interdependencies among the concepts that comprise a given domain, because these interdependencies determine to a large extent the order of acquisition of these concepts. I have argued that the concepts that comprise the domain of astronomy have a relational structure that influences their order of acquisition. One example is the interrelationship that exists between the earth-shape and gravity concepts. Students cannot have an understanding of the earth's shape without some understanding of the concept of gravity, for otherwise they cannot understand how it is possible for people to live on the sides and bottom of the spherical earth without falling off. Another is the interrelationship between the earth's shape and the explanation of the day/night cycle already discussed.

Given the problems children have with the notion of a spherical earth and the importance that this concept has for understanding practically any other concept in the domain of astronomy, one would think that astronomy instruction would start with a unit on the earth's shape. This was not the case in any of the astronomy units in the four science series I investigated. There was a unit on the earth in one of them, but the critical information regarding the earth's shape was covered in just one sentence stating that "the earth looks like a globe." Surprising also was the lack of any discussion about the notion of gravity in these units. As already mentioned, some discussion of the notion of gravity is essential for students to understand how people can live at the bottom of the earth.

In the series I examined, astronomy instruction started with some attempt to explain the day/night cycle. In one series, an explanation of the day/night cycle that included a demonstration with a globe and a flashlight was attempted at the kindergarten level. Another series started with an attempt to explain the phases of the moon at Grade 1! In a third series, instruction on astronomy started at Grade 2 with an explanation of both the day/night cycle and of the phases of the moon.

As discussed earlier, many of the children in our studies failed to understand the explanation of the day/night cycle in terms of the axis rotation of the earth because they had a synthetic model of the earth's shape. Failure to understand the scientific explanation of the day/night cycle may also result from students' lack of information about the relative size, movement, and location of the earth, the sun, and the moon in the solar system. At least 80% of the children in our studies who explained the day/night cycle in terms of the earth's axis rotation had a scientific mental model of the solar system. When the relevant concepts are not presented in a hierarchical fashion, with attention paid to cover the necessary prerequisites, superficial memorization or misunderstandings are likely to occur.

In a recent experiment (Vosniadou, in press), I examined third graders' explanations of the day/night cycle before and immediately after they read a text on the cycle from two leading science series. The results showed that only 2 out of 60 children changed from incorrect explanations in the pretest to correct explanations in the posttest. Most children simply added the information that the earth moves (in an unspecified way) to their existing model, or created a synthetic model.

If the explanation of the day/night cycle is not a good starting point for an astronomy curriculum, the explanation of the phases of the moon is even worse. In fact, it is hard to find a concept covered in the elementary astronomy curriculum that would be more difficult. Most of the college undergraduates in our adult studies of astronomy do not know how to explain the phases of the moon correctly.

It is not a bad idea to have a unit on the moon, following a unit on the earth's shape and gravity, in which it is pointed out that while the moon appears to change shape, it does not in fact do so. However, at this level it would be better to concentrate on explaining the concept of reflection and how the moon gets its light from the sun in more detail, as children do not really understand how the moon reflects the sun's light. Teaching children about the source of the moon's light as well as about its motion and its location relative to the earth and the sun would set the stage for a full explanation of the phases of the moon at a later grade.

Sensitivity to Students' Mental Models

I have argued that students use whatever knowledge they have in their knowledge base to construct mental models they use to make sense of incoming information. I have also shown that often these models are very different from those expected from the scientifically literate adults in our society. For instruction to be successful, we must be sensitive to students' alternative mental models. It is only when we understand how students think that we will be able to lead them slowly to form increasingly more and more sophisticated mental models, closer to those that are culturally accepted.

This sensitivity to students' alternative mental models was often absent in the astronomy texts I investigated. In fact, it was often the case that these texts were written in such a way as to reinforce students' intuitive or synthetic mental models rather than replace them with scientific ones. For example, in units on the sun or the moon, I often found expressions such as "the sun went down," which reinforce students' belief that the sun moves in an up/down fashion and causes the day/night cycle.

In one series, a chapter entitled "The Blue Planet" starts with the passage that appears in Table 4.

[Insert Table 4 about here.]

This passage is very consistent and in fact reinforces the dual-earth mental model described earlier. Children who hold this mental model believe that there are two earths: a flat one on which people live (often referred to as "the ground") and a spherical one (known as "earth"), which is a planet located up in the sky (see Vosniadou & Brewer, submitted). The wording of this passage allows the following interpretation: You are in a spacecraft traveling from the flat ground toward the planet earth. When you look out of the spacecraft, you see the spherical earth, which is a blue planet.

In the same unit, a lesson on the seasons is linked to the earth's tilt without explaining how the seasons really occur, saying only that when the earth tilts toward the sun it is summer and "when it is farther away from the sun, we have winter." This section is shown in Table 5.

[Insert Table 5 about here.]

The wording of this explanation for the seasons can reinforce two common misconceptions. One is the misconception held by most children and adults alike that winter is caused because the earth *is* farther away from the sun in the winter. This misconception is caused by the literal interpretation of the sentence, "When it *is* farther away from the sun, we have winter," instead of the intended interpretation "When it is *tilted* farther away from the sun, we have winter."

Even if the reader of this passage understands that the earth is tilted farther away from the sun in the winter, the wording of the tilt explanation could lead fairly directly to the "wobbly tilt" misconception of the seasons according to which the direction of the earth's tilt changes because the earth "wobbles" from one side to the other as it revolves around the sun.

Finally, Table 6 shows the last page from a unit that attempts to explain the day/night cycle in terms of the "turning" of the earth. On the previous page, it is said that "the turning earth causes night to change to day." On this page, the children see a picture of the turning earth that shows both axis rotation and revolution around the sun. The text continues to refer to the "turning" earth without explaining how the earth turns and which of the two movements shown in the picture causes the day/night cycle. This text reinforces the misconception often found in elementary school children that the alteration of day and night is caused because the earth revolves around the sun every 24 hours.

[Insert Table 6 about here.]

Presenting Counterintuitive Information as a Fact

The astronomy units I have investigated often introduce counterintuitive information as a fact. For example, students are simply told that "the earth rotates around its axis," "the sun is much bigger than the earth," or that "the sun is a star" without an explanation of how it is possible for the earth to move when we do not feel any movement; how it is possible for the sun to be bigger than the earth when it appears to be much smaller; and how it is possible for the sun to be a star when stars appear in the sky only at night, have a different shape than the sun, are smaller, etc.

It is important in instruction to distinguish new information that is consistent with prior knowledge from new information that runs contrary to prior knowledge. When the new information is consistent with prior knowledge, then it can be easily incorporated into existing conceptual structures. This type of information will most likely be understood, even if it is presented as a fact without any further explication. However, when the new information runs contrary to students' existing conceptual structures, simply presenting the new information as a fact may not be adequate. In this situation students seem to have two courses of action available to them. One is simply to add the new fact to their existing conceptual structures. In this case, the new representation will be internally inconsistent. The other is to distort the new fact to make it consistent with the existing structure. In this case, the result will be a misconception. For the counterintuitive information to be understood, students must restructure the conceptual structures they have to make them consistent with the new information. This cannot be done, however, in the absence of additional information. Students must be either given a new explanatory structure explicitly or must be put in some situation where it is possible to discover it.

Let us examine, for example, the situation where a child is told that "*the sun is hot like fire*" and the situation where a child is told that "*the sun is a very hot star,*" as is the case in the text entitled "Our Sun," which appears in Table 7.

[Insert Table 7 about here.]

The information that the sun is hot may be new to young children, but it is consistent with their phenomenal experience and can be easily added to the existing conceptual structures, even if it is stated as a fact. The information that the sun is a star cannot, however, be added to a young child's knowledge base without some significant reorganization taking place. Stars look very different from the sun, they appear much smaller, and are in the sky during the night with the moon. For these reasons, children think that stars are different kinds of things than the sun. Most of the fifth- and sixth-grade children we have studied believe that stars are more like the moon than the sun (see Vosniadou & Brewer, 1990). If we want children to understand that the sun is a star, we must explain to them why stars look smaller than the sun and why they appear in the sky only during the night.

Addressing Students' Misconceptions and Entrenched Beliefs

Many researchers in science education stress the importance of identifying and confronting students' misconceptions. In this section, I will focus on two issues regarding the treatment of misconceptions in science curricula. The first has to do with the relationship between misconceptions and entrenched beliefs and the second with the instructional treatment of misconceptions and entrenched beliefs.

The relationship between misconceptions and entrenched beliefs. I agree with many science educators that it is important to identify the misconceptions students have and to explain to them how these misconceptions differ from the scientific explanations. However, I also believe that focusing on misconceptions alone may not always provide a solution to the problem of restructuring. According to my analysis, misconceptions (or what I call synthetic mental models) are formed because students are trying to reconcile certain entrenched beliefs with culturally accepted scientific views. If I am correct, misconceptions will not be replaced with the culturally accepted models if the entrenched belief(s) that underlie them are not removed.

Consider as an example the case of a student who has formed the synthetic model of a hollow earth. If the instruction focuses on the misconception, it could be pointed out to this student that the earth is not hollow and that people live *on* the spherical earth, outside. This type of instruction will not, however, address the real problem the student has with the concept of a spherical earth. The hollow-sphere misconception provides students with a solution to their problems of how it is possible for people to live at the bottom and sides of the spherical earth without falling and how it is possible for the ground to appear to be flat when it is round. What students need in order to abandon their synthetic

model of a hollow sphere is instruction that focuses on their underlying entrenched beliefs. That is, a lesson on gravity and a lesson on how round things can sometimes appear to be flat. Otherwise, one misconception will be followed with another and students will remain confused.

Identifying and addressing students' entrenched beliefs is also a more efficient and parsimonious way of dealing with misconceptions than is addressing each misconception individually. This is the case because (as was shown before) a very small number of entrenched beliefs, acting as constraints on the kinds of mental models students can form, can lie at the root of a very large number of misconceptions. I believe that the success of designing curricula that promote conceptual restructuring depends to a large extent on the success (a) of basic research to identify the entrenched beliefs that cause misconceptions, and (b) of instructional methods to make students re-interpret these beliefs within a different explanatory framework.

Instructional treatment of misconceptions and entrenched beliefs. What are the best instructional methods to replace entrenched beliefs with a different explanatory framework? This is a very important question and more research is needed before deciding how to best answer it. At this point, it appears that curricula and instruction that aim at replacing entrenched beliefs with a different explanatory framework must:

1. create some conditions for students to question their entrenched beliefs. This can be done by putting students in circumstances where they have to evaluate empirical evidence that is contrary to their beliefs;

2. provide a clear explanation of scientific concepts, preferably in the form of conceptual models or analogies; and

3. demonstrate how the new conceptual models provide a better account of the available empirical observations than the entrenched beliefs.

Creating Metaconceptual Awareness

Finally, it is important to design curricula and instruction that aim at increasing students' metaconceptual awareness. Students often find scientific explanations incredible to believe and see no reason why they should question their beliefs, which are more consistent with their everyday experience. It is important when we teach science to provide students with situations that will make them realize that their beliefs about the world are not "true facts" but theoretical constructions that may be subject to falsification.

This could be done by showing students, in relevant laboratory activities, that there are certain empirical observations that are not consistent with their beliefs, and that if their beliefs are modified their empirical adequacy will increase. Instructional programs that aim at enriching students' experiential knowledge without making them aware of the fundamentally theoretical nature of their activity fail to create this necessary metaconceptual awareness.

Conclusions

I have argued that when we design curricula aimed at restructuring students' prior knowledge, we must pay particular attention both to the contents and the methods of instruction. Regarding the contents of instruction, particular attention must be paid to the sequence in which the various concepts that comprise a given domain are introduced. I have argued that instruction that is consistent with the sequence of acquisition of these concepts will be more successful than instruction that is not. In addition, students need to be provided with adequate explanations of scientific concepts, explanations that take into account their mental models and address their entrenched beliefs. Finally, particular attention should be paid to providing students with situations that make them realize that what they

consider as facts about the world may be interpretations subject to falsification and that there are, sometimes, good reasons for replacing the beliefs they have formed on the basis of their everyday experience with a different explanatory framework.

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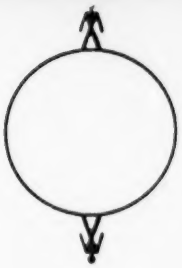
Author Note

An earlier version of this report appeared in *The Journal of Curriculum Studies, 23*(3), 219-237.

Sphere



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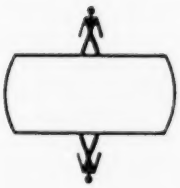

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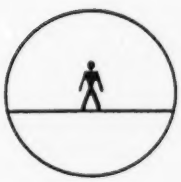
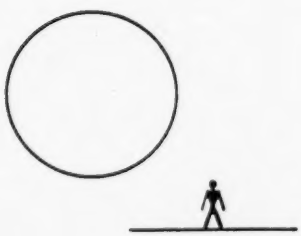


Dual Earth



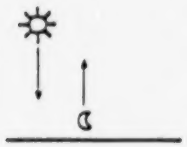
Disc

Rectangle

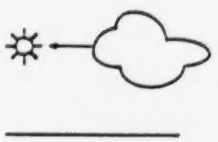
Mental Models of the Earth

Table 1

The sun moves down on the ground behind hills and the moon goes up

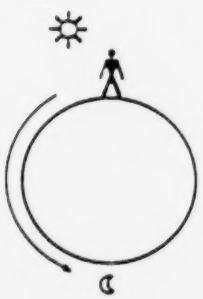


Clouds cover the sun



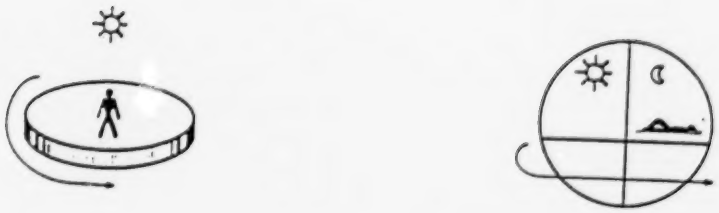
The sun moves from the sky to outer space

The earth's rotation causes our side of the earth to face the moon



Explanation of the Day/Night Cycle

Table 2



(a) (b)

Explanations of the day/night cycle in terms of the earth's axis rotation for (a) a disc-earth mental model and (b) a hollow-earth mental model

Table 3

THE EARTH AND THE MOON

10-1.

The Blue Planet

Pretend you are in a spacecraft. You are traveling toward the earth. When you look out the window of the spacecraft, you see a blue planet. Do you know why the earth looks blue?

Table 4

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The sun warms the earth. Even though the sun is far away, the heat from the sun keeps the earth warm. The part of the earth that is tilted nearest the sun will be the warmest. This is why we have seasons. We have summer when the part of the earth where we live is tilted toward the sun. When it is farther away from the sun, we have winter. What season is it now where you live? Is the earth tilted toward or away from the sun? How do you know?

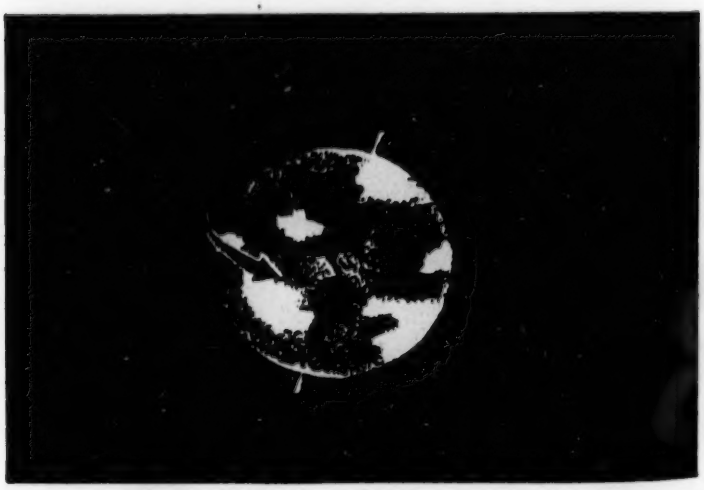

Table 5

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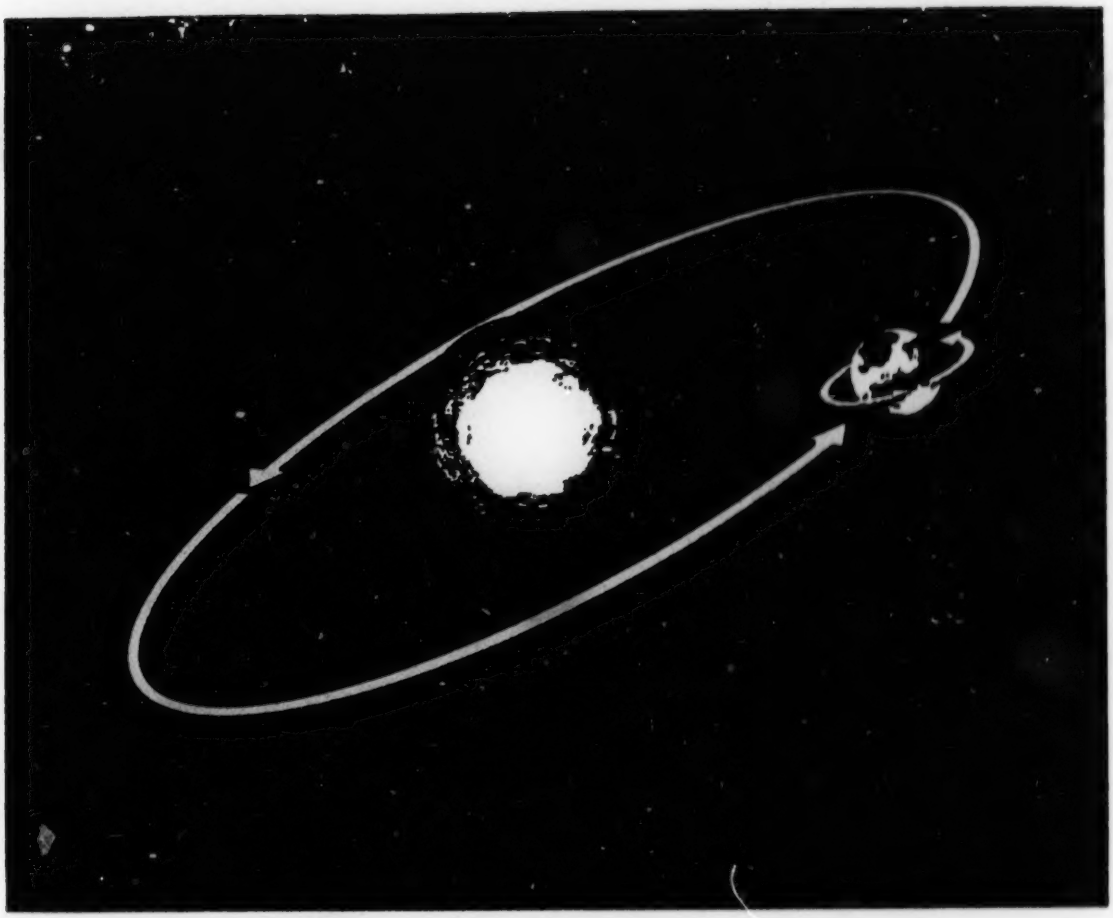

The earth is always turning. It never stops turning. You cannot see or feel it turning. It makes one complete turn every day. How many times does the earth turn in a week?

Table 6

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Our Sun

There are many stars in the night sky. On a clear night you can see thousands of them. Do you know that these stars are like the sun? The **sun** is a very hot star. It is the star closest to the earth. It is the only star we can see in the daytime sky. The sun is very important to us.

Table 7